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6. AUTHOR(S)

Michael M. Micci

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Aerospace Engineering
The Pennsylvania State University
233 Hammond Bldg.
University Park, PA 16802

8. PERFORMING ORGANIZATION REPORT NUMBER

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CONTRIBUTIONS OF ATOMIZATION, VAPORIZATION AND COMBUSTION TO LIQUID ROCKET ACOUSTIC ENERGY

Grant No. F49620-94-1-0384

P.I.: Michael M. Micci
Graduate student: Mena Ferraro

Department of Aerospace Engineering
The Pennsylvania State University
University Park, PA 16802

ABSTRACT

Acoustic oscillations were induced in a sub-scale liquid rocket engine that burned liquid oxygen and gaseous hydrogen as propellants. The oscillations in the chamber were forced by a rotating gear just downstream of the nozzle throat. High frequency data was acquired for pressure and velocity via a pressure transducer and a magnetic flowmeter. The magnetic flowmeter obtains the acoustic gas velocity by measuring the voltage induced by the ionized combustion products moving through an externally imposed magnetic field. A cross correlation was performed on the velocity and pressure signals to determine the amplitude and phase difference of the two signals.

NOMENCLATURE

B magnetic flux density (T)
E electric field strength (V/m)
f_k frequency (Hz)
L distance between electrodes in the magnetic flowmeter (m)
n_p number of data points in average
$\hat{S}(f)$ power spectra
V voltage induced across electrodes in the magnetic flowmeter (V)
U, u velocity of combustion gases (m/s)

Greek Symbols
α proportionality constant for the magnetic flowmeter
$\Delta\phi$ phase error (°)
γ coherence

Subscripts
p pressure
pu pressure and velocity correlation
u velocity

INTRODUCTION

Prior research has proven the validity of several techniques for analyzing combustion instabilities in liquid propellant rocket engines including the time lag concept and models of the actual combustion mechanisms[1]. Yet another technique defines response functions to determine combustion stability within the rocket chamber. When analyzing the stability of rocket engines, researchers determine the pressure- and velocity-coupled response functions. Each response function is a complex number which determines the response of the various processes within the rocket engine with respect to the unsteady pressure or velocity.

One method of determining the response functions is to measure the unsteady properties of the gases inside the rocket chamber. One technique used for solid propellants is the magnetic flowmeter. Micci and Caveny[2] determined the real part of the pressure-coupled response function in a forced longitudinal wave motor which burned solid propellants. A spinning gear at the exit of the rocket motor nozzle induced acoustic oscillations (unsteady pressure and velocity) within the motor. The experiments proved the validity of using a magnetic flowmeter in solid rockets independent of the propellant type. Wilson and Micci[3] implemented a similar experimental setup to measure the real and imaginary parts of the pressure-coupled response function. Response functions were found for two formulations of AP/HTPB composite propellants. Cauty, Comas, Vuillot and Micci[4] used a similar experimental setup to determine the real part of the pressure-coupled response function. This experiment deduced the response functions from the steady and unsteady pressure and the unsteady velocity. One experiment, completed by Holme[5], measured the steady velocity in the exhaust of a liquid rocket with an electromagnetic flowmeter. The flowmeter used the alternating magnetic field from an electromagnet. Holme concluded that the electromagnetic flowmeter worked properly for several types of liquid propellants excluding a hydrogen peroxide monopropellant due to its low flame temperature.

EXPERIMENTAL APPROACH

Sub-Scale Rocket Chamber

A sub-scale rocket chamber previously used to measure liquid oxygen drop size and velocity[6] was modified to include a segment which could measure unsteady pressure and velocity[7,8]. The design of the chamber was based on a single injection element of the Space Shuttle Main Engine (SSME) Preburner. Liquid oxygen was injected coaxially inside a surrounding gaseous hydrogen stream. The chamber was modular in design and consisted of six segments including, the injector, ignitor segment, pressure release mechanism, magnetic flowmeter segment, window segment and nozzle. The total length of the chamber was 0.377 m (14.8 in) and the width of the hexagonal cross-section from one face to the other was 0.028 m (1.12 in).

Acoustic oscillations were induced within the chamber by rotating a gear immediately downstream of the nozzle as shown in Figure 1. When the rotating teeth of the gear partially obstructed the flow from the converging nozzle the throat area was periodically varied. The gear was constructed of steel and contained 28 teeth. The height and width of the teeth, 0.0127 m (0.5 in), were approximately the same size as the diameter of the nozzle throat, 0.0132 m (0.52 in). A protective steel box was constructed to contain and divert the exhaust gases away from the rocket chamber. The gear was driven by an explosion-proof motor which in turn was driven by an invertor. The invertor remotely controlled the frequency of the signal transmitted to the motor which controlled the motor speed.

Magnetic Flowmeter

Unsteady pressure and velocity measurements were acquired within the magnetic flowmeter segment of the rocket chamber. This segment contained a port for a high frequency pressure transducer to measure unsteady pressure and a magnetic flowmeter to measure unsteady velocity at 0.139 m (5.47 in) downstream of the injector. The magnetic flowmeter consisted of a permanent magnet and two electrodes. The interaction between the magnetic field and the electrically conducting combustion gases within the chamber induced a voltage across the electrodes.

From electromagnetic theory the electric field, E, is defined as $E = U \times B$ where U is the flow velocity of an electrically conducting fluid and B is the magnetic field. When two metal rods are placed in the electric field perpendicular to the direction of a gas flow a potential difference is generated. This potential difference is proportional to the product of the flow velocity and the magnetic field according to Faraday's Law[9]: $V = \alpha ULB$. In this equation α is a proportionality constant of the order 1, L is the distance between the electrodes and V is the induced voltage.

A cross sectional view of the magnetic flowmeter used in the experiments is shown in Figure 2. The path of the combusting gases passed through the magnetic flowmeter segment perpendicular to the page. The magnetic field was produced by a horseshoe permanent magnet with a gap density of 0.19 Tesla. The electrodes protruded into the chamber approximately 0.003 m (0.12 in) with the distance between them approximately 0.022 m (0.88 in).

Experimental Procedure

The hot fire combustion tests were conducted at the Cryogenic Combustion Laboratory at the Pennsylvania State University. For each test, high frequency pressure and velocity data were acquired from the piezoelectric pressure transducer and magnetic flowmeter. The gear which modulated the exhaust was rotated at a frequency between 2500 and 2700 teeth per second. These frequencies were near the first longitudinal resonance frequency of the chamber. The mean pressure for the tests ranged from 2.6 to 3.0 MPa (375 to 425 psi).

EXPERIMENTAL RESULTS

The voltage difference measured by the magnetic flowmeter was converted into velocity as described in the previous section. The dimensionless proportionality constant, α, could not be determined and was assumed to be 0.5. For most of the tests the pressure signal oscillated between ±0.28 MPa (±40 psi) and the velocity signal had an average value between ±1.5 m/s (±5 ft/s). The pressure and velocity time records were transformed into the frequency domain by a Fast Fourier Transform (FFT)[10] to calculate the Power Spectrum Density (PSD) of the pressure, $\hat{S}_p(f)$, and velocity, $\hat{S}_u(f)$, signals in the frequency domain. Figures 3 and 4 are plots of the PSD of the pressure and velocity signals for a test with a constant gear frequency of 2669 teeth per second. The data is plotted in three-dimensions on a waterfall plot to show dependence with time. Each horizontal line on the plot represents data taken over 0.178 seconds. The pressure PSD clearly shows the acoustic oscillations in the chamber at the frequency induced by the gear. Both the first and second harmonics are visible in the graph at approximately 2670 and 5340 Hz. As expected the velocity PSD is much noisier, however the induced frequency is still visible at both the first and second harmonics corresponding to the pressure wave.

The pressure and velocity signals were correlated to obtain the Cross Spectrum Density (CSD) between the pressure and velocity signals in the frequency domain. Figure 5 is a waterfall plot of the CSD for the same test shown in Figures 3 and 4. The CSD shows the pressure and velocity signals to be related at the gear forcing frequency and the plot is much less noisy than the waterfall plot of the velocity PSD. The CSD provided a means to calculate the phase difference between the pressure and velocity signals. The phase was calculated from the real and imaginary parts of the complex CSD frequency signal

The error associated with performing the CSD is determined by the coherence function as defined in Equation 1 where f_k is the frequency corresponding to the gear forcing frequency. The coherence is a ratio of the averaged CSD to the product of the measured pressure PSD and the measured velocity PSD. The coherence lies between the values of zero and one and equals one for a noiseless signal. Measured and averaged data have a coherence less than one. The coherence predicts the error in the CSD phase calculation. Equation 2 defines the phase error where n_p is the number of points over which the phase is averaged.

$$\gamma_{pu}^2(f_k) = \frac{\overline{\left|\hat{S}_{pu}(f_k)\right|}^2}{\hat{S}_p(f_k)\hat{S}_u(f_k)} \qquad (1)$$

$$\Delta\phi = \frac{\sqrt{1-\gamma_{pu}^2}}{\left|\gamma_{pu}\right|\sqrt{2n_p}} \qquad (2)$$

CONCLUSION

A rotating gear near the exit of the nozzle of a sub-scale liquid rocket chamber induced acoustic oscillations within the chamber. Pressure transducers measured the mean and unsteady pressures within the chamber. A magnetic flowmeter equipped with a permanent magnet measured the unsteady velocity of the combusting gases. The experiments have proven that the magnetic flowmeter is capable of acquiring unsteady velocity data within a gaseous hydrogen/liquid oxygen rocket chamber.

The unsteady pressure and velocity time signals were transformed into the frequency domain with a Fast Fourier Transform. The two frequency signals were then correlated to determine the frequency at which both of the signals were oscillating, i.e. the forcing frequency of the rotating gear in the experiment. After averaging the phase difference between the unsteady pressure and velocity was determined at this frequency. The phase error was calculated from the coherence function at the forcing frequency.

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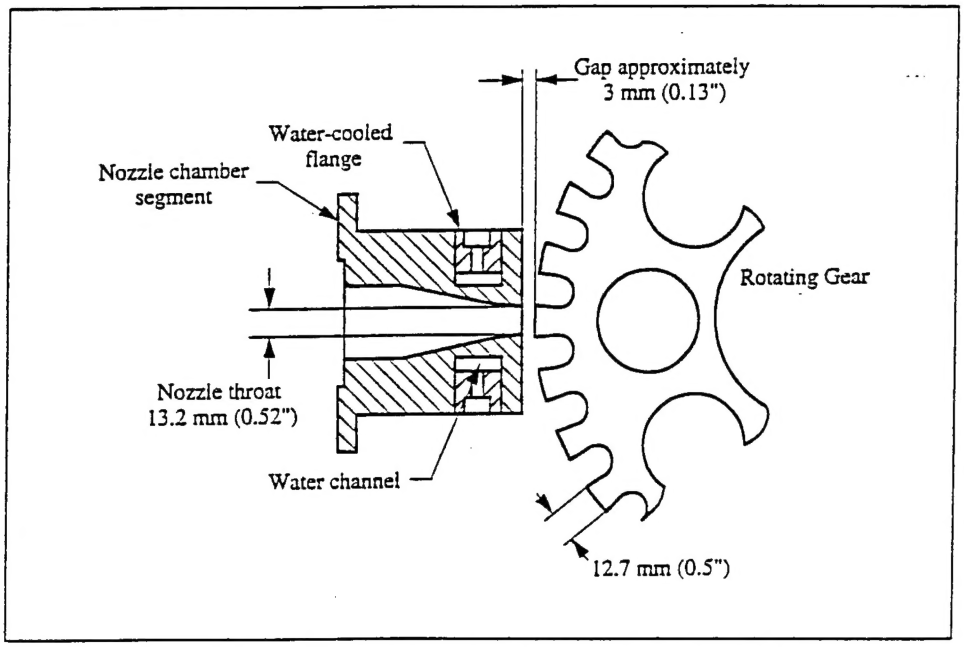

Figure 1 - Gear and nozzle setup

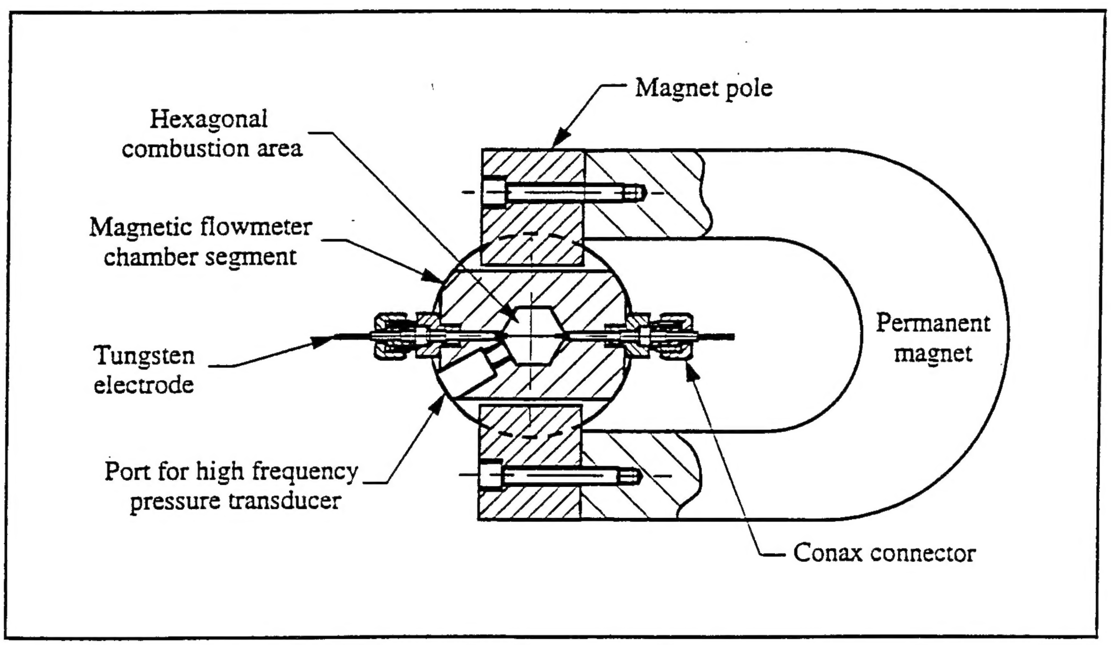

Figure 2 - Magnetic flowmeter chamber segment

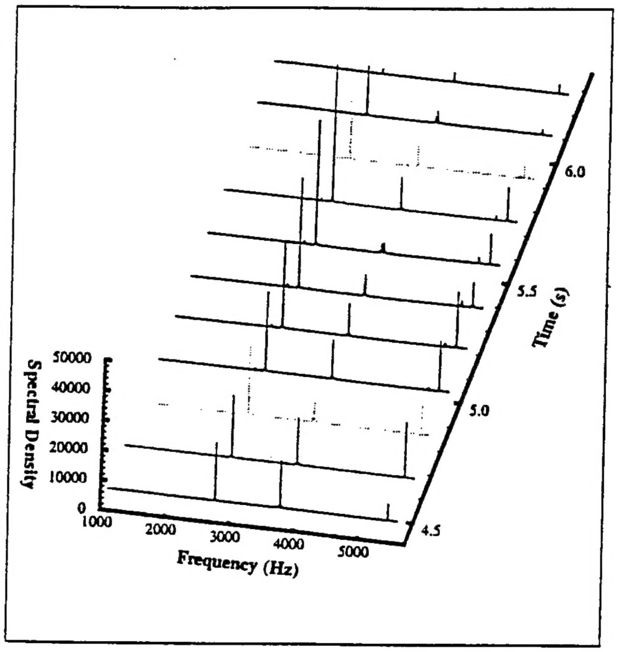

Figure 3 - Unsteady pressure power spectral density

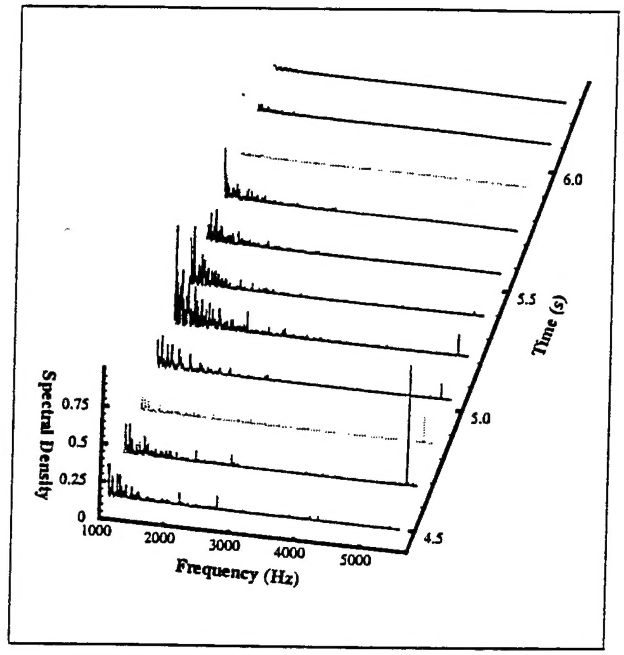

Figure 4 - Unsteady velocity power spectral density

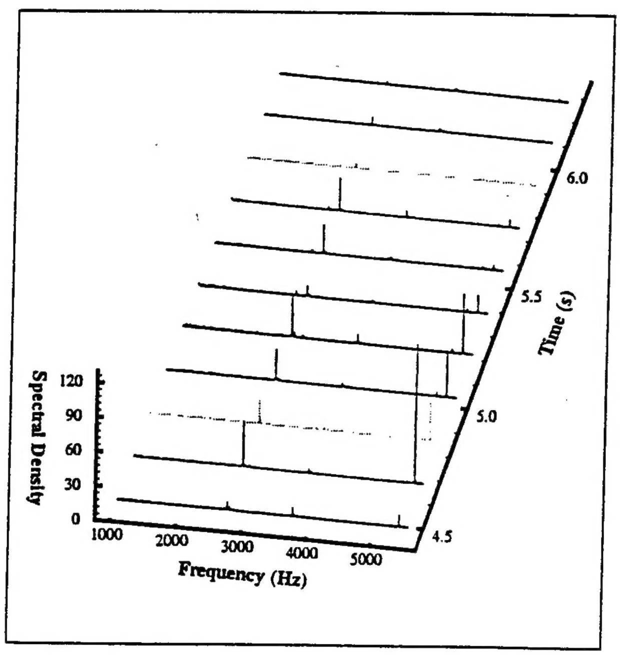

Figure 5 - Unsteady pressure and velocity cross spectral density